A Study of LLC Converter with Buck Converter for CC-CV Charging

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Abstract – For having switching frequency equal to resonant tank frequency in LLC converter, a unity voltage gain can be achieved over the entire loading conditions but it is not suitable for the Constant Current-Constant Voltage (CC-CV) battery application. Also, the voltage gain characteristic of LLC converter is frequency dependent. For battery charging application, a wide range of switching frequency is required for supplying constant current, charging the battery with its varying load characteristic. It causes above and below resonant frequency operation which causes losses and noise. As result, it is proposed to make use of a buck converter at the output of LLC converter for regulating the charging current and voltage for battery charging application.

Keywords - LLC converter, Buck converter, CC-CV battery charging, closed-loop control

I. Introduction

For on-board charger, it is common to use a resonant converter for providing the isolation for safety and high output power level by employing a resonant tank [1]. One of the well-known topologies is the full-bridge LLC converter with a full-bridge rectifier. Its construction is simple because only a resonant capacitor is required for resonating with the leakage inductance of the high-frequency transformer. By using the inherent leakage inductance of the transformer, a resonant inductor can be eliminated. Cost and component count can be reduced.

A complicated control scheme, such as variable frequency control, is inevitably adopted an LLC converter [2]. Other advanced control schemes for applying to the wide-range input voltage and/or output voltage application can be found also [3]. However, for this paper application, the input voltage is fixed to 220Vac/50Hz rectified to 312Vdc, there is no need for the design of the LLC converter to take into consideration of a wide range of input voltage. In that case, it is chosen to use fixed frequency switching for the LLC converter with open-loop control, cascaded with a buck converter at its output, for regulating the charging current and voltage in CC-CV battery charging. It will be an easy implementation for a CC-CV battery charger.

Apart from that, using a buck converter simplifies the design of the LLC converter. For a typical LLC converter design, it is required to optimize the ratio of leakage inductance with magnetizing inductance for the high-frequency transformer [4]. This design procedure can be saved so that it is only required for choosing the resonant frequency of the resonant tank. With fixed switching frequency in the LLC converter as resonant frequency, its output voltage will be fixed independent of load condition. And it can be regulated by the duty cycle of the buck converter, for CC-CV battery charging.

For a LLC converter, the resonant capacitor will be selected for resonating with the leakage inductance of the LLC transformer. Its capacitance owns tolerance which will cause the failure of resonant condition of the LLC converter [5]. As a result, the output voltage of LLC converter may not be load-independent. By using buck converter for regulating the output of LLC converter, it allows the variation of the output voltage from the LLC converter, ensures CC-CV charging.

One more advantage of using buck converter is that, as mentioned before, the requirement for the transformer design of the LLC converter is released. So, it allows the primary winding and secondary winding of the transformer wound on two separate ferrite cores. It gives the chance for making a contactless connector for Electric Boat charger. Because when an electric boat lies at the pier, people concerns about getting an electric shock near the water when charging a boat by a metal-conductive charger connector. As a result, it will be a good use if a contactless charger connector can be made.

This paper is organized into three sections, Section II gives the modeling of LLC converter for estimating the output voltage variation, Section III gives a simulation model of overall circuit performance for showing the CC-CV mode charging. Section IV gives the experiment setup for showing the performance of the LLC converter with buck converter.

II. Modeling of LLC converter in resonant state

A typical circuit of a full-bridge LLC converter with a full-bridge rectifier is shown in Fig. 1 [4].

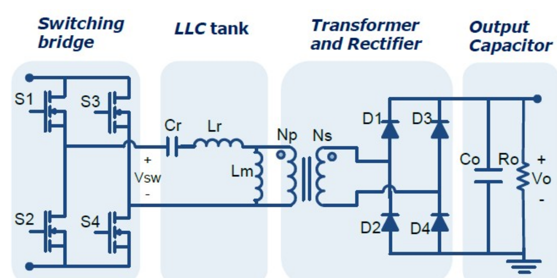


Fig. 1: Circuit connection of a full-bridge LLC converter with full-bridge rectifier [4]

By optimization, the equivalent circuit of Fig. 1 can be obtained as shown in Fig. 2 [4].

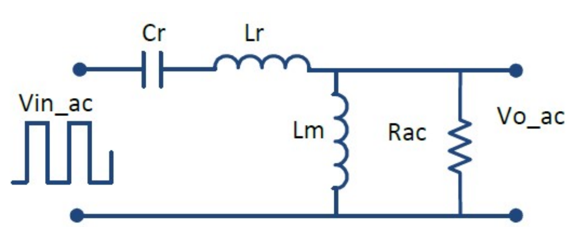


Fig. 2: Equivalent circuit of a full-bridge LLC converter with full-bridge rectifier [4]

From Fig. 2, the magnitude of the output-input voltage ratio of the equivalent circuit can be derived as shown in Eqn. (1) [4].

$$K(Q,m,F_x)=\left|\frac{V_{o\_ac}(s)}{V_{in\_ac}(s)}\right|=\frac{F_x^{\,2}(m-1)}{\sqrt{\left(m\cdot F_x^{\,2}-1\right)^2+Fx^2\cdot\left(F_x^{\,2}-1\right)^2\cdot(m-1)^2\cdot Q^2}} \quad (1)$$

Where,

$Q=\dfrac{\sqrt{L_r/C_r}}{R_{ac}}$ Quality factor

$R_{ac}=\dfrac{8}{\pi^2}\cdot\dfrac{N_P^{\,2}}{N_S^{\,2}}\cdot R_o$ Reflected load resistance

$F_x=\dfrac{f_s}{f_r}$ Normalized switching frequency

$f_r=\dfrac{1}{2\pi\sqrt{L_r\cdot C_r}}$ Resonant frequency

$m=\dfrac{L_r+L_m}{L_r}$ Ratio of total primary inductance to resonant inductance

Based on Eqn. (1), the magnitude of voltage gain is plotted under the circuit parameters shown in Table 1.

Table 1: Circuit Parameters

Circuit Parameters	value
Resonant inductance, L_r	562uH
Resonant capacitor, C_r	4.7nF
Resonant frequency, f_r	100kHz
Magnetizing inductance, L_m	1.37mH
Turns ratio, Np:Ns	76:78
R_o	11.25Ω to 19.125Ω

For the R_o range, this application is going to supply a lithium battery with 144V/80Ah capacity. The constant charging current is selected to be 8A, and the minimum voltage of the battery is set to 90V, the constant voltage charging is selected to be 153V. As a result, R_o will be in the range of 11.25Ω to 19.125Ω under CC mode.

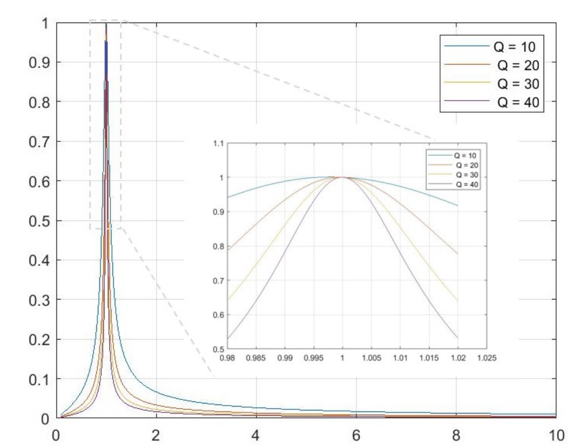


Fig. 3: Magnitude of Output-input voltage gain curve

From Fig.3, it is shown that when switching frequency is the same as resonant frequency ($F_x = 1$), no mater under which load condition, the voltage gain remains to be 1. Then, for the buck converter, the LLC converter behaves as a fixed output voltage source. The buck converter is controlled by varying its duty cycle for the CC-CV charging battery.

III. Simulation of LLC converter with Buck converter

A. LLC converter only

A simulation model is created by the software PSIM™ as shown in Fig. 4. Fig. 5 shows the fixed output voltage characteristic of the LLC converter when $f_s = f_r$. It is observed that the output voltage of the LLC converter is independent of load condition. Fig. 6 shows the H-bridge output voltage and current under R_0 = 11.25Ω and R_0 = 19.125Ω, in an open loop control for 1:1 fixed output voltage. The resonant state of the LLC converter is achieved.

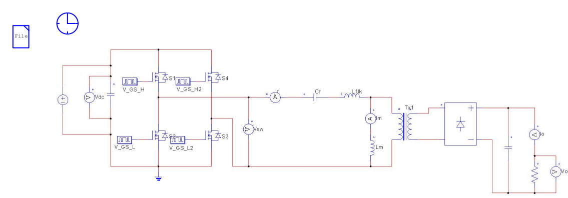
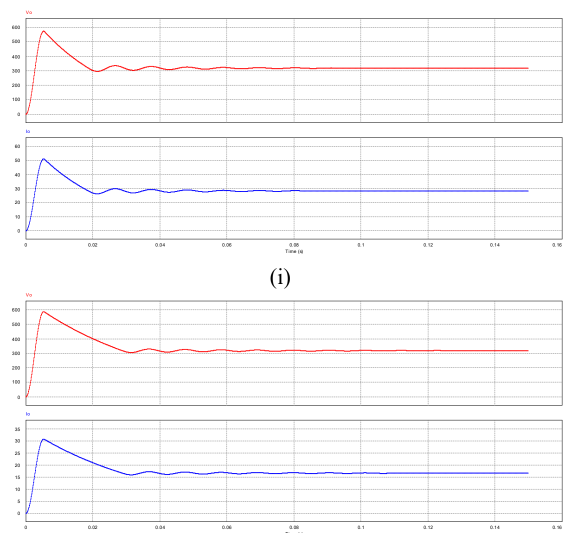


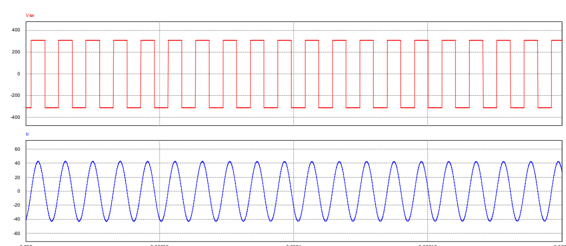
Fig. 4: Simulation model of the full-bridge LLC converter with full-bridge rectifier



(i)

(ii)

Fig. 5: Output voltage and output current simulation result (i) R_o = 11.25Ω (ii) R_o= 19.125Ω, under open loop condition



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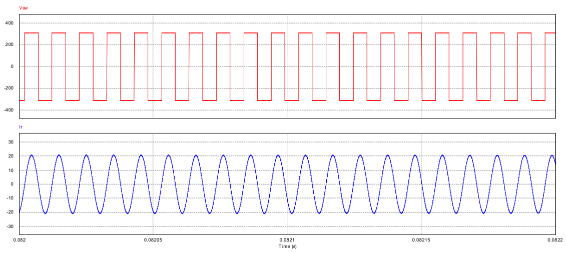


(ii)

Fig. 6: The H-bridge output voltage and current simulation result (i) R_o = 11.25Ω (ii) R_o= 19.125Ω, under open loop condition

B. LLC converter with buck converter in closed-loop form

Under the closed-loop control, a simple comparator circuit of inductor current and output current comparison, is implemented. Fig. 7 shows the simulation model based on the circuit parameter defined in Table 2 for the buck converter. Fig. 8 shows the output voltage of LLC converter, charging voltage and charging current when (i) R_o = 11.25Ω, (ii) R_o= 19.125Ω. Fig. 9 shows the H-bridge output voltage and current under R_0 = 11.25Ω and R_0 = 19.125Ω, in a closed loop control for 8A output current. The resonant state of the LLC converter is achieved.

From the simulation results, it is proved that under $f_s = f_r$, the buck converter is getting a fixed input voltage at its input side. As a result, the buck converter does not require to adapt a wide range of input voltage and no need for a complicated control scheme.

Table 2: Circuit Parameters for the Buck converter

Circuit Parameters	value
Inductor, L	550uH
Input capacitor, C_{in}	100uF
Switching frequency, f_r	100kHz
Output capacitor, C_{out}	330uF

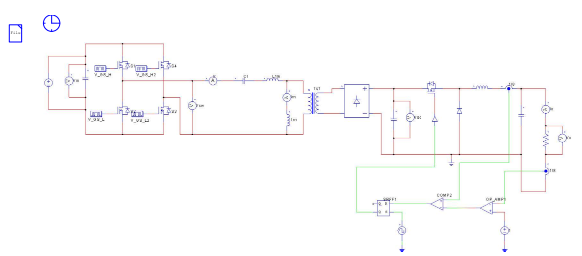
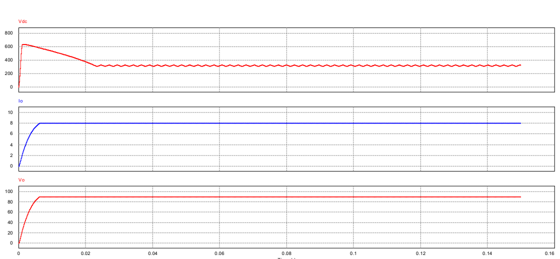


Fig. 7: Simulation model of LLC converter with Buck converter in closed-loop form



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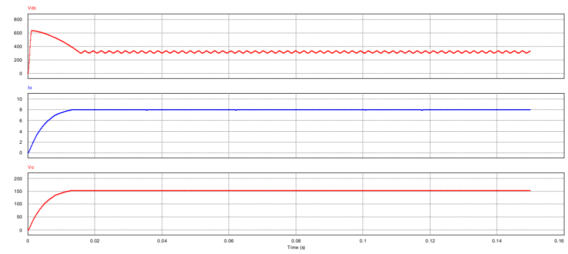
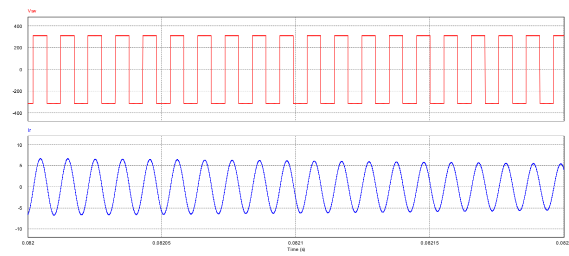


(ii)

Fig. 8: Output voltage of LLC converter, output voltage and output current simulation result (i) R_o = 11.25Ω (ii) R_o= 19.125Ω, under closed loop condition



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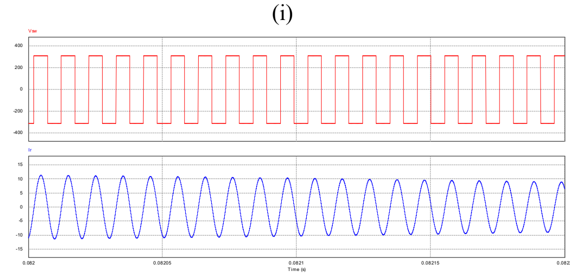


(ii)

Fig. 9: The H-bridge output voltage and current simulation result (i) Ro = 11.25Ω (ii) Ro= 19.125Ω, under closed loop condition

C. LLC converter with buck converter in control of C code

Under the closed-loop control, it is inevitable for using C code to control the switching mode of the CC-CV mode charging. In the simulation model, a C program block was used to emulate the microcontroller which controls the charger operation. The CC-CV mode charging operation was implemented with PI compensation according to the voltage and current feedback. Fig. 10 shows the simulation model based on the design of C code. Fig. 11 shows its output voltage and output current. It is proved that the program is worked for switching the converter to CV code with decreasing output current.

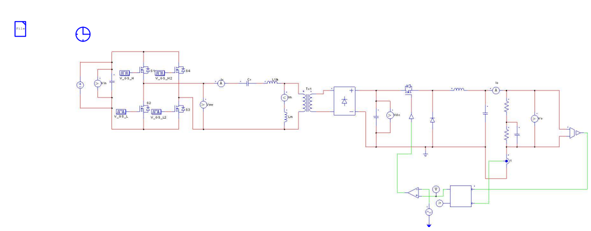


Fig. 10: Simulation model of LLC converter with Buck converter in closed-loop form by C code

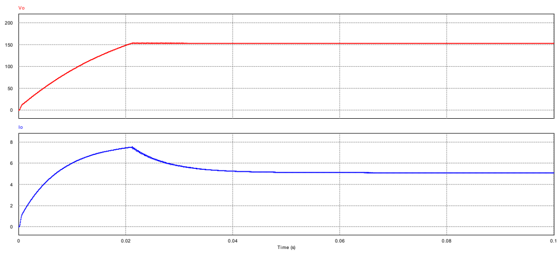
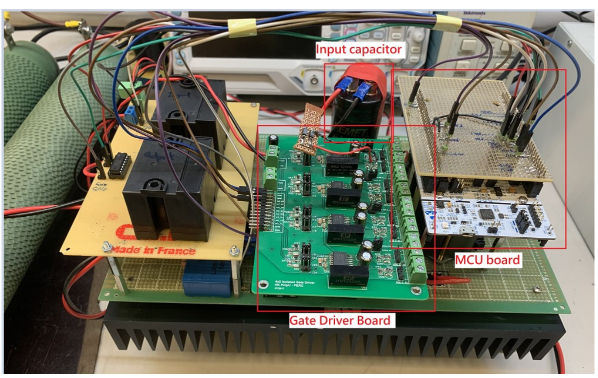


Fig. 11: The output voltage and current simulation result, under closed loop control by C code

IV. Experimental Results of the Proposed Circuit

A buck converter prototype is built and shown in Fig. 12. Experimental waveforms at CC mode current = 6A and 8A are shown in Fig.13. Table 3 shows the efficiency of the buck converter. Under the constant current charging at 8A, the buck converter can achieve 96.5% efficiency.

Fig. 14 shows the separable primary and secondary winding for using the high-frequency transformer of the LLC converter, its parameter as shown in Table. 1. The conductors of the split-core transformer and the coupling point are completed sealed. This design aims to be used in a water environment for charging eliminating the risk of electric shock.



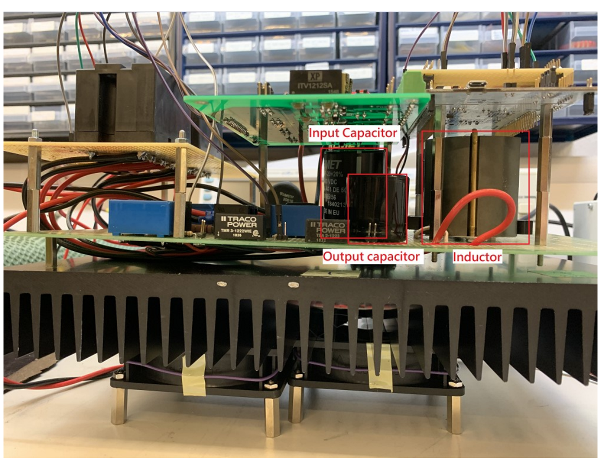
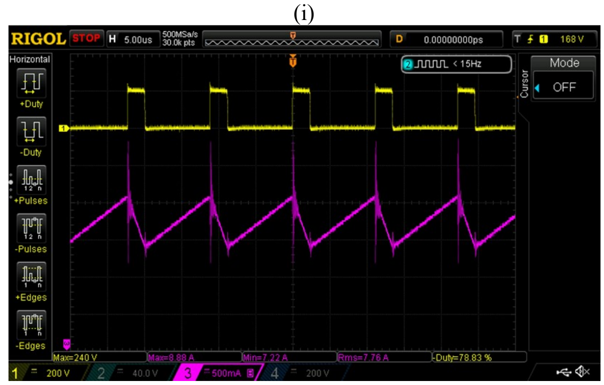


Fig. 12: A prototype of the buck converter

(i)



(ii)

Fig. 13: Drain-source voltage of high side MOSFET and inductor current waveforms (i) CC mode current = 6A (ii) 8A

Table 3: Efficiency of the Buck converter

CC mode current	P_{out}	P_{loss}	Eff.
2A	77W	10W	88.5%
4A	310W	20W	94.0%
6A	691W	39W	94.7%
8A	1141W	42W	96.5%

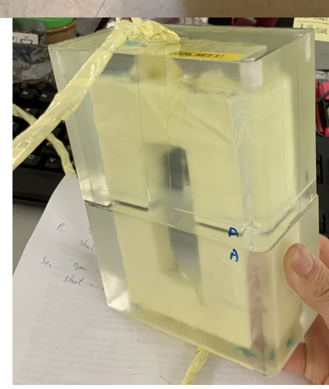


Fig. 14: Separable primary and secondary winding used in the LLC converter

V. CONCLUSION

This paper presents an LLC converter with a buck converter for CC-CV charging. The simulation and prototype are presented for proving that the idea is achievable and attains the highest efficiency at 96.5%. Besides, the hardware of the separable primary and secondary winding for using as a high-frequency transformer of the LLC converter is demonstrated for showing the possibility of producing a water-proof connector for battery charging application under water.

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